

# Indirect Violation of CP, T and CPT in the $B_d$ -system <sup>1</sup>

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## Abstract

The problem of indirect violation of discrete symmetries CP, T and CPT in a neutral meson system can be described using two complex parameters  $\varepsilon$  and  $\delta$ , which are invariant under rephasing of meson and quark fields. For the  $B_d$  system, where the width difference between the physical states is negligible, only  $\text{Re}(\delta)$  and  $\text{Im}(\varepsilon)$  survive. As a consequence, the traditional observables constructed for kaons, which are based on flavour tag, are not useful for the analogous study in this system. We describe how using a CP tag and studying *CP-to-flavour* transitions of the  $B$  mesons, we may build asymmetries, alternative to those used for the kaon, which enable us to test T and CPT invariances of the effective hamiltonian for the  $B_d$  system.

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The problem of indirect violation of discrete symmetries CP, T and CPT in a neutral meson system can be described using two complex parameters  $\varepsilon$  and  $\delta$ , which are invariant under rephasing of meson and quark fields. For the  $B_d$  system, where the width difference between the physical states is negligible, only  $\text{Re}(\delta)$  and  $\text{Im}(\varepsilon)$  survive. As a consequence, the traditional observables constructed for kaons, which are based on flavour tag, are not useful for the analogous study in this system. We describe how using a CP tag and studying *CP-to-flavour* transitions of the  $B$  mesons, we may build asymmetries, alternative to those used for the kaon, which enable us to test T and CPT invariances of the effective hamiltonian for the  $B_d$  system.

## 1. Introduction

The time evolution of a neutral meson system is governed by an effective hamiltonian [1]. The problem of indirect violation of discrete symmetries refers to the non-invariance of this hamiltonian under the corresponding operations.

For the kaon system, this study has been performed by the CP-LEAR experiment [2] from the preparation of definite flavour states  $K^0$ - $\bar{K}^0$ . These tagged mesons evolve in time and their later decay to a semileptonic final state projects them again on a definite flavour state. The study of this *flavour-to-flavour* evolution allows the construction of observables which violate CP and T, or CP and CPT.

Contrary to what happens in the kaon case, for the  $B_d$ -system the width difference  $\Delta\Gamma$  between the physical states is expected to be negligible. In this system the T- and CPT-odd observables proposed for kaons, which are based on flavour tag, vanish. but, making use of CP tag, the  $B_d$  entangled states can be used to construct alternative observables which are sensitive to T and CPT independently of the value of  $\Delta\Gamma$  [3].

## 2. The parameters

In the neutral  $B$ -meson system the physical states are a linear combination of  $B^0$  and  $\bar{B}^0$ . If they are written in terms of CP eigenstates, one has to introduce two complex parameters,  $\varepsilon_{1,2}$ , to

describe the CP mixing.

$$|B_{1,2}\rangle = \frac{1}{\sqrt{1+|\varepsilon_{1,2}|^2}} \left[ |B_{\pm}\rangle + \varepsilon_{1,2} |B_{\mp}\rangle \right], \quad (1)$$

where  $|B_{\pm}\rangle \equiv \frac{1}{\sqrt{2}}(I \pm CP)|B^0\rangle$ . Then  $\varepsilon_{1,2}$  are invariant under rephasing of the meson states, and physical when the CP operator is well defined [4].

Alternatively, one may use the parameters  $\varepsilon \equiv (\varepsilon_1 + \varepsilon_2)/2$  and  $\delta \equiv \varepsilon_1 - \varepsilon_2$ , whose interpretation in terms of symmetries is simpler.

Discrete symmetries impose different restrictions on the effective mass matrix,  $H = M - \frac{i}{2}\Gamma$ : CPT invariance requires  $H_{11} = H_{22}$ , T invariance imposes  $\text{Im}(M_{12}CP_{12}^*) = \text{Im}(\Gamma_{12}CP_{12}^*) = 0$ , and CP conservation requires both conditions to be simultaneously satisfied. Furthermore, in the exact limit  $\Delta\Gamma = 0$ , customary for the  $B_d$ -system, both  $\text{Re}(\varepsilon)$  and  $\text{Im}(\delta)$  vanish. Therefore we have four real parameters which carry information on the symmetries of the effective mass matrix

- $\text{Re}(\varepsilon) \Rightarrow$  CP and T violation, with  $\Delta\Gamma \neq 0$ ;
- $\text{Im}(\varepsilon) \Rightarrow$  CP and T violation;
- $\text{Re}(\delta) \Rightarrow$  CP and CPT violation;
- $\text{Im}(\delta) \Rightarrow$  CP and CPT violation,  $\Delta\Gamma \neq 0$ .

## 3. The entangled state: CP tag

In a  $B$  factory operating at the  $\Upsilon(4S)$  peak, correlated pairs of neutral  $B$ -mesons are pro-

duced through  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ . The special features of this system can be used to study CP [5] and CPT [6] violation in  $B$  mesons.

In the CM frame, the resulting  $B$ -mesons travel in opposite directions, each one evolving with the effective hamiltonian. The  $B\bar{B}$  state has definite  $L = 1$ ,  $C = -$  and  $\mathcal{P} = -$ , being  $\mathcal{P}$  the operator which permutes the spatial coordinates, so that the initial state may be written as

$$|i\rangle = \frac{1}{\sqrt{2}} \left( |B^0, \bar{B}^0\rangle - |\bar{B}^0, B^0\rangle \right) \quad (2)$$

The correlation between both sides of the entangled state holds at any time after the production. As a consequence, one can never simultaneously have two identical mesons at both sides of the detector. This permits the performance of a flavour tag: if at  $t = 0$  one of the mesons decays through a channel, such as a semileptonic one, which is only allowed for one flavour of the neutral  $B$ , the other meson in the pair must have the opposite flavour at  $t = 0$ .

The entangled  $B-\bar{B}$  state can also be expressed in terms of the CP eigenstates  $|B_{\pm}\rangle$  as

$$|i\rangle = \frac{1}{\sqrt{2}} \left( |B_-, B_+\rangle - |B_+, B_-\rangle \right) \quad (3)$$

Thus it is also possible to carry out a CP tag, once we have a CP-conserving decay into a definite CP final state, so that its detection allows us to identify the decaying meson as a  $B_+$  or a  $B_-$ .

In Ref. [7] we described how this determination is possible and unambiguous to  $\mathcal{O}(\lambda^3)$ , which is sufficient to discuss both CP-conserving and CP-violating amplitudes in the effective hamiltonian for  $B_d$  mesons. Here  $\lambda$  is the flavour-mixing parameter of the CKM matrix [8]. The determination is based on the requirement of CP conservation, to  $\mathcal{O}(\lambda^3)$ , in the  $(sd)$  and  $(bs)$  sectors. To this order, however, CP-violation exists in the  $(bd)$  sector, and it can be classified by referring it to the CP-conserving direction. A  $B_d$  decay that is governed by the couplings of the  $(sd)$  or  $(bs)$  unitarity triangles, or by the  $V_{cd}V_{cb}^*$  side of the  $(bd)$  triangle, will not show any CP violation to  $\mathcal{O}(\lambda^3)$ . We may say that such a channel is free from direct CP violation. Examples are  $J/\Psi K_S$ , with  $\text{CP} = -$ , and  $J/\Psi K_L$ , with  $\text{CP} = +$ .

To extract information on the symmetry parameters we may study the time evolution of the entangled state (2) and its decay into a final configuration  $(X, Y)$ . In our notation,  $X$  is the decay product observed on one side of the detector at a certain time, and  $Y$  the product detected on the opposite side after a  $\Delta t$ .

We will only consider here decay channels  $X, Y$  which are either flavour or CP conserving. Then the final configuration  $(X, Y)$  corresponds to a certain transition at the mesonic level, i.e. the  $B$  state tagged by the  $X$  decay evolves for a period  $\Delta t$  and is then projected into a flavour or CP eigenstate by means of the  $Y$  decay.

## 4. The asymmetries

By comparing the probabilities corresponding to different processes we build time-dependent asymmetries that allow the extraction of the relevant parameters. The observables can be classified into three types.

### 4.1. Flavour-to-flavour genuine asymmetries

If one detects semileptonic decays on both sides of the detector, then the transition at the meson level is of the kind *flavour-to-flavour*. The mesonic transitions for such a final configuration appear in Table 1, where  $\ell^\pm$  represents the final decay product of a seminclusive decay  $B \rightarrow \ell^\pm X^\mp$ . From these processes we can construct

Table 1  
*Flavour-to-flavour* transitions

$(X, Y)$	Transition
$(\ell^+, \ell^+)$	$\bar{B}^0 \rightarrow B^0$
$(\ell^-, \ell^-)$	$B^0 \rightarrow \bar{B}^0$
$(\ell^+, \ell^-)$	$\bar{B}^0 \rightarrow \bar{B}^0$
$(\ell^-, \ell^+)$	$B^0 \rightarrow B^0$

two non-trivial asymmetries, which are the analogous, in the  $B$ -system, to the traditional observables used for kaons. The first two processes in Table 1 are conjugated under CP and also under

T, then we may construct a genuine asymmetry by comparing the corresponding intensities

$$A(\ell^+, \ell^+) \approx \frac{\text{Re}(\varepsilon)}{1+|\varepsilon|^2}. \quad (4)$$

On the other hand, the last two processes in Table 1 are related by a CP or a CPT transformation. Therefore, the corresponding asymmetry,

$$A(\ell^+, \ell^-) \approx -2 [\text{Ch} \frac{\Delta\Gamma\Delta t}{2} + \cos(\Delta m\Delta t)]^{-1} \left[ \text{Re} \left( \frac{\delta}{1-\varepsilon^2} \right) \text{Sh} \frac{\Delta\Gamma\Delta t}{2} - \text{Im} \left( \frac{\delta}{1-\varepsilon^2} \right) \sin(\Delta m\Delta t) \right], \quad (5)$$

is also a genuine CP and CPT observable.

In both cases, the resulting asymmetry vanishes unless  $\Delta\Gamma \neq 0$ . Thus measuring a small value for these observables does not impose a straightforward bound on the size of symmetry violation, because the vanishingly small  $\Delta\Gamma$  of  $B$ -mesons would hide any symmetry breaking effect.

#### 4.2. CP-to-flavour genuine asymmetries

We may construct alternative asymmetries making use of the CP eigenstates, which can be identified in this system by means of a CP tag. If the first decay product,  $X$ , is a CP eigenstate produced along the CP-conserving direction, and  $Y$  is a semileptonic channel, then the mesonic transition corresponding to the configuration  $(X, Y)$  is of the type *CP-to-flavour*. The order of appearance of both final states matters, because for the reverted configuration,  $(Y, X)$ , we have a *flavour-to-CP* transition. In Table 2 we show the mesonic transitions, with their related final configurations, connected by genuine symmetry transformations to  $B_+ \rightarrow B^0$ , i.e.  $(J/\Psi K_S, \ell^+)$ . Comparing the

Table 2  
Transitions connected to  $(J/\Psi K_S, \ell^+)$ .

$(X, Y)$	Transition	Transformation
$(J/\Psi K_S, \ell^-)$	$B_+ \rightarrow \bar{B}^0$	CP
$(\ell^-, J/\Psi K_L)$	$B^0 \rightarrow B_+$	T
$(\ell^+, J/\Psi K_L)$	$\bar{B}^0 \rightarrow B_+$	CPT

intensity of  $(J/\Psi K_S, \ell^+)$  with each of them we construct three genuine asymmetries. Next, we show the results to linear order in  $\delta$  and in the

limit  $\Delta\Gamma = 0$ .

$$A_{\text{CP}} = -2 \frac{\text{Im}(\varepsilon)}{1+|\varepsilon|^2} \sin(\Delta m\Delta t) + \frac{1-|\varepsilon|^2}{1+|\varepsilon|^2} \frac{2\text{Re}(\delta)}{1+|\varepsilon|^2} \sin^2 \left( \frac{\Delta m\Delta t}{2} \right), \quad (6)$$

is the CP odd asymmetry, which has contributions from T-violating and CPT-violating terms. The first term, odd in  $\Delta t$ , is governed by the T-violating  $\text{Im}(\varepsilon)$ , whereas the second term,  $\Delta t$  even, is sensitive to CPT violation through the parameter  $\text{Re}(\delta)$ .

$$A_{\text{T}} = -2 \frac{\text{Im}(\varepsilon)}{1+|\varepsilon|^2} \sin(\Delta m\Delta t) \left[ 1 - \frac{1-|\varepsilon|^2}{1+|\varepsilon|^2} \frac{2\text{Re}(\delta)}{1+|\varepsilon|^2} \sin^2 \left( \frac{\Delta m\Delta t}{2} \right) \right], \quad (7)$$

the T asymmetry, needs  $\varepsilon \neq 0$ , and includes CPT even and odd terms. Moreover, in the limit we are considering, turns out to be purely odd in  $\Delta t$ .

$$A_{\text{CPT}} = \frac{1-|\varepsilon|^2}{1+|\varepsilon|^2} \frac{2\text{Re}(\delta)}{1+|\varepsilon|^2} \frac{\sin^2 \left( \frac{\Delta m\Delta t}{2} \right)}{1 - 2 \frac{\text{Im}(\varepsilon)}{1+|\varepsilon|^2} \sin(\Delta m\Delta t)}, \quad (8)$$

is the CPT asymmetry. It needs  $\delta \neq 0$ , and includes both even and odd time dependences, so that there is no definite symmetry under a change of sign of  $\Delta t$ .

Measuring the presented asymmetries (6)-(8) with good time resolution, so to separate even and odd  $\Delta t$  dependences, should be enough to determine the parameters  $\frac{2\text{Im}(\varepsilon)}{1+|\varepsilon|^2}$  and  $\frac{1-|\varepsilon|^2}{1+|\varepsilon|^2} \frac{2\text{Re}(\delta)}{1+|\varepsilon|^2}$ , which govern CP, T violation and CP, CPT violation, respectively, in the  $B_d$  mixing.

Contrary to what happened in the case of flavour tag, the CPT and T asymmetries based on a CP tag do not vanish due to the smallness of  $\Delta\Gamma$ . Instead, they provide a set of observables which could separate the parameters  $\delta$  and  $\varepsilon$ .

#### 4.3. CP-to-flavour non-genuine asymmetries

The asymmetries defined in the previous paragraphs are genuine observables, since each of them compares the original process with its conjugated under a certain symmetry and is thus odd under the corresponding transformation. Nevertheless the measurement of all those quantities requires to tag both  $B_+$  and  $B_-$  states. The last needs, from the experimental point of view, a good reconstruction of the decay  $B \rightarrow J/\Psi K_L$ ,

not so easy to achieve as for the corresponding  $J/\Psi K_S$  channel.

But it is also possible to construct useful asymmetries from final configurations  $(X, Y)$  with only  $J/\Psi K_S$ . In Table 3 we show the different

Table 3  
Final configurations with only  $J/\Psi K_S$ .

$(X, Y)$	Transition	Transformation
$(J/\Psi K_S, \ell^-)$	$B_+ \rightarrow B^0$	CP
$(\ell^+, J/\Psi K_S)$	$\bar{B}^0 \rightarrow B_-$	$\Delta t$
$(\ell^-, J/\Psi K_S)$	$\bar{B}^0 \rightarrow B_-$	$\Delta t + \text{CP}$

transitions we may study from such final states. From the comparison between  $(J/\Psi K_S, \ell^+)$  and each process in the table we can construct three asymmetries. The first one will correspond to the genuine CP asymmetry  $A(J/\Psi K_S, \ell^-) = A_{\text{CP}}$ . We find that, in the exact limit  $\Delta\Gamma = 0$ ,  $\Delta t$  and T operations become equivalent, so that  $A(\ell^+, J/\Psi K_S) \equiv A_{\text{T}}$  and  $A(\ell^-, J/\Psi K_S) \equiv A_{\text{CPT}}$ . But these asymmetries are not genuine. They do not correspond to true T- and CPT-odd observables, for the processes we are comparing are not related by a symmetry transformation. This implies that the presence of  $\Delta\Gamma \neq 0$  may induce non-vanishing values for them, even if there is no true T or CPT violation. But even if that is the case, it is possible to separate out the different parameters, if good enough  $\Delta t$  is provided [9].

## 5. Conclusions

We present an overview of the possibilities to explore indirect violation of CP, T and CPT in a neutral meson system from the quantities that  $B$ -factories can measure. The asymmetries analyzed here exploit their time dependences in order to separate out two different ingredients: on one hand CP and T violation, described by  $\varepsilon$ , and on the other CP and CPT violation, given by  $\delta$ . Such a study is possible, even if  $\Delta\Gamma = 0$ , if one goes beyond *flavour-to-flavour* transitions and makes use of CP tags.

We classify the observables into three different types:

- Genuine asymmetries for T or CPT violation, based on *flavour-to-flavour* transitions at the meson level, which need  $\Delta\Gamma \neq 0$ .
- Genuine observables, based on the combination of flavour and CP tags, which do not need  $\Delta\Gamma$ .
- Making use of the equivalence between  $\Delta t$  and T reversal operations for  $\Delta\Gamma = 0$ , we have also considered non genuine observables, involving only the hadronic decay  $J/\Psi K_S$ .

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